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PLANT LIFE MANAGEMENT STRATEGIES FOR PRESSURIZED HEAVY WATER REACTORS

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본 보고서를 "중수로발전로의 수명관리"의 기술보고서로 제출합니다.

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1. GENERAL DESCRIPTION OF SYSTEM

CANDU reactor is using natural uranium and heavy water (D_2O) as fuel and moderator, respectively, as opposed to light water reactors. A reactor assembly of CANDU 6 is shown in Figure 1. Calandria is a horizontally mounted cylindrical reactor vessel that supports 380 fuel channels via end fittings. Reactivity control units are inserted from the top and the side of the calandria. There are two primary coolant loops each of which carries 50% of thermal powder generated. Each loop consists of two inlet and outlet headers and two steam generators. Moderator system is separated from the coolant heavy water system to solely provide neutron moderation.

A fuel channel assembly consists of a calandria tube and a pressure tube. The pressure tube holds 12 fuel bundles and acts as part of the pressure boundary. Spacers are located between calandria tube and pressure one to prevent contacting each other. Both tubes are fixed to the calandria with end fittings. Annulus between the calandria tube and the pressure tube is filled with cover gas CO_2 which provides thermal insulation.

The volume between the calandria and calandria tubes is filled with heavy water moderator. The heat deposited in moderator is removed by two moderator heat exchangers. Moderator system is operated in principle at an atmospheric pressure.

Another distinctive feature of CANDU reactors is that refueling is done during full power operation. Eight out of twelve fuel bundles contained in a pressure tube are replaced during refueling, each of which consists of 37 fuel pins assembled in a short cylindrical bundle (102 mm Φ x 495 mm L).

There are 24 CANDU reactors currently in operation worldwide as shown in Table 1; 1 unit in Argentina, 22 units in Canada and 1 unit in Korea. The oldest unit is Pickering unit 1 in Canada of 25 years old. Most of the CANDU reactors are experiencing some problems related to pressure tubes after the operation of about 10-15 years. Therefore, a major concern of the life management in CANDU reactors is focusing on the pressure tube issue.

2. CATEGORIZATION OF COMPONENTS (CANDU 6)

CANDU reactor can be grouped into three design categories such as Ontario Hydro Pickering units, CANDU 6, and Ontario Hydro Bruce and Darlington units but the description is made here only of CANDU 6. The CANDU reactor consists of three major systems; Reactor Assembly, Moderator System and Heat Transport System. However, among them, the system most significantly affecting the reactor life is the reactor assembly.

2.1 Reactor Assembly

Reactor assembly consists of fuel channel assemblies, calandria/end shield support assembly and reactivity control units. The 380 fuel channel assemblies containing fuel and heavy water coolant pass horizontally through the calandria vessel. The calandria vessel is provided with two end shield supports while each end shield support consists of a flexible stainless steel support shell/annular support plate combination welded to a carbon steel embedment ring. The calandria and end shields are located in the concrete reactor vault that is steel lined and is filled with light water to serve as a thermal shield and cooling medium for the vault concrete. The calandria shell is provided with nozzles for the attachment of the vertical and horizontal reactivity control thimbles, pressure relief pipes and the moderator recirculation pipes. Thus, fast reactor shutdown is achieved by inserting shutoff rods through those thimbles or by injecting liquid poison into the moderator.

2.2 Moderator System

Moderator system is designed to control and remove the heat from the calandria. It consists of two interconnected circuits each of which contains one pump and two heat exchangers circulating the heavy water moderator through the calandria. The heavy water moderator enters the calandria through two sets of four nozzles located on the opposite sides of the calandria shell and exits through two nozzles at the bottom of the calandria. The moderator system also acts as a medium for dispersion of reactivity control agents and the liquid neutron absorber of shutdown system by using poisoning material.

2.3. Primary Heat Transport System

The primary heat transport system consists of piping, shutdown cooling systems, pressure and inventory control system, feed, bleed & relief system and emergency coolant injection system. This system recirculates pressurized heavy water, D_2O in two piping loops through the fuel channels to remove heat, which is transferred to the secondary system in the steam generators producing steam. The piping system lies mostly within the containment, and has a design life of 30 years. The pressure and inventory of the primary heat transport system is maintained by a pressurizer and a balanced feed and bleed flow. In case of a loss of coolant accident, the emergency cooling injection system is actuated to refill the main primary heat transport system.

3. LIST OF KEY COMPONENTS

The key components affecting the CANDU reactor life mainly are the calandria vessel and the fuel channel components, i. e., pressure tubes, end fittings, calandria tubes and spacers. A fuel channel assembly is shown in Figure 2.

3.1. Pressure Tube

Pressure tubes are located co-axially in the center of the calandria tubes, holding the fuel bundles and providing heavy water coolant passage. Pressure tubes are kept separated from the inner surface of the calandria tube by the spacers. Materials to be used in pressure tube should have properties such as low neutron absorption cross section, high strength, high corrosion resistance and low hydrogen absorption. Zircaloy-2 was used as pressure tube material in the early CANDU reactors but has been replaced by Zr-2.5 wt.% Nb alloy since the accidents in Pickering units.

Failures in CANDU reactors are known to be related mostly to the pressure tubes. This is why most researches have focused on the issues and the innovation of the pressure tubes. Their aims have been to increase fracture toughness of pressure tubes and reduce their susceptibility to delayed hydride cracking (DHC) by optimizing the manufacturing procedures.

3.2. Calandria Tube

Calandria tube is an integral part of the reactor structure that is connected to the calandria side tube by means of roll-expansion. Zircaloy-2 is still used as calandria tube material for its good corrosion resistance and excellent neutron economy.

3.3. End Fitting

The pressure tube is joined to the end fittings by roll joint. Heavy water coolant for heat transportation is introduced to the pressure tube through the end fitting which allows the path for loading and unloading fuel bundles as well. The end fittings of the both sides, in and out, are housed by the shield plugs. The outboard face of each end fitting is put into the condition of sealed connection to the fuelling machine when fuels are loaded and unloaded. The end fittings are sealed by the channel closures when fuelling machines are not in connection with the channel. Modified 403 stainless steel of high corrosion resistance is used for the end fittings. The end fitting liner tube is made of seamless type ASTM-A268, Grade-410 stainless steel.

3.4. Fuel Channel Spacer

Spacers between pressure tube and calandria one act to support the pressure tube and keep it separated from the calandria. Spacers are made of Inconel X-750 alloys and are in shape of close-coiled helical spring. In the early design, there were only two loose type spacers installed. Since it is now known that the displacement of the spacers induces the contact between pressure tube and calandria, leading to the pressure tube failure by DHC, the number of the spacers has increased to four instead of two. Furthermore, the spacers are tightly fit to the outer surface of the pressure tube to prohibit their displacement.

3.5. Calandria

Calandria is horizontal cylindrical vessel with its ends closed by the end shields. The assembly is made of austenitic stainless steel and has the primary functions of containing the heavy water moderator, and supporting incore components of the vertical and horizontal reactivity control units. The calandria vessel is comprised of a main shell with smaller sub-shells at each end.

4. AGING MECHANISM OF KEY COMPONENTS

Pressure tubes are exposed to the temperature of 313 °C, the pressure of 11 MPa and the neutron flux of 3.7×10^{13} n/cm^2/sec in operation. These severe operational conditions bring changes in material properties and dimension due to irradiation damage, leading to the degradation of pressure tubes. Further, as corrosion of pressure tubes proceeds, pressure tubes pick up hydrogen in accompany with corrosion.

All Zircaloy-2 pressure tubes of Pickering units 1 and 2 were replaced after the operational period of about 10 years due to the concern of unexpected tube deformation by neutron irradiation and fast tube rupture by DHC. Those tubes in Pickering units 3 and 4 also was replaced before reaching their 30 design life due to the concern of the contact between pressure tube and calandria tube and because of too short bearing length. Therefore, primary aging concerns in CANDU pressure tubes are delayed hydride cracking, irradiation enhanced deformation and decrease in fracture toughness.

4.1. Delayed Hydride Cracking of Pressure Tube

4.1.1. Hydrogen Concentration and Deuterium Ingress

Solubility limits of hydrogen and deuterium in zirconium are very low as shown in figure 3. Hydride is formed due to the low solubility at low temperatures. At the reactor operating temperatures, hydrides are formed only when the extent of hydrogen picked up exceeds the terminal solid solubility, called "TSS", which is the hydrogen equivalent (hereafter called "Heq") concentration at the temperature. TSS varies from 40 to 70 ppm at the operating temperatures, depending on the tube temperatures. However, if the content of hydrogen is low enough to prevent the formation of any hydrides at the operating temperatures, then DHC will not occur. In other words, the best way to prevent the tube failures associated with the delayed hydride cracking is not for hydrides to form. Therefore, it is important to minimize the initial content of hydrogen.

As opposed to 5 to 15 ppm of hydrogen in the early manufactured tubes, the recently improved tube manufacturing technology leads the initial hydrogen content to decrease to less than 5 ppm [1]. Figure 4 shows the hydrogen contents of the tubes manufactured in accordance with the updated AECL specification. As a result, it increases the time it takes to form hydrides by about 20 years assuming that its maximum Heq pick-up rate during operation is 1 ppm/year [2].

High temperature heavy water passing through the pressure tubes corrodes the pressure tube, resulting in the increase of the oxide film thickness [2,3]. Though the corrosion does not affect the tube life due to negligible loss of metal, the deuterium pick-up accompanied in the corrosion process is more important from the standpoint of DHC. Since Zircaloy-2 had higher deuterium pick-up rate, the pressure tubes of Zircaloy-2 was considered not to guarantee over 30 years of safe operation. However, the pressure tube of Zr-2.5 % Nb picks up only 5 % of the hydrogen generated from corrosion. Therefore, it takes much longer time for Zr-2.5 % Nb pressure tube to form hydrides. However, since many failures reported so far are known to be related to DHC as shown in Table 2 and no CANDU unit has ever been operated to the 30 years of design life, the deuterium ingress rate has to be monitored continously to assure that the deuterium ingress rate is kept low enough at the end of life. Deuterium content of the pressure tubes is to be monitored periodically by taking samples by scraping the inner surface of the currently operating tubes or by the periodic removal of pressure tubes.

The rolled joints are the most susceptible to delayed hydride cracking than any other regions of a pressure tube due to the higher deuterium ingress rate as shown in figure 5 and high residual tensile stress [4]. The higher rate of deuterium ingress at the rolled joints is attributed to the galvanic corrosion at the crevice between the pressure tube and the end fittings. Furthermore, the outer surfaces of tube ends are damaged in the process of roll joining, enhancing the deuterium ingress rate because they cannot act as effective barriers any longer. Since the outlet temperature is higher than the inlet one, the deuterium ingress rate is higher at the outlet end than at the inlet end. Thus, the empirical model for a H_{eq} profile may allow to predict that H_{eq} at the rolled joint region will reach TSS before the

30 year design life [4]. This empirical model, however, is applicable only to certain units, not to all CANDU reactors. Thus, it is concluded that sufficient amount of in-reactor data are needed from every different unit.

4.1.2. Hydride Blister

Local accumulation of hydrogen/deuterium takes place in the region of high tensile stress and at the cold spots where a pressure tube touches a cold calandria tube by sagging. If the amount of accumulated hydrogen at those regions exceeds TSS, hydrides become precipitated and crack by DHC. Thus, the worst consequence of DHC is leakage of pressure tubes, not rupture. Such Leak-Before-Break (LBB) behavior has been demonstrated in Pickering units 3 and 4 where the crack was developed at the rolled joints. However, in 1983, a pressure tube of Zircaloy-2 in the fuel channel G16 of Pickering unit 2 ruptured without any prior detectable leakage [5]. This incident showed that brittle hydride blisters can develop at the cold spots where a pressure tube was sagged into the calandria tube surrounding it and LBB may not occur before the tube ruptures at power.

Since this accident, all CANDU reactors have used Zr-2.5 wt. % pressure tubes, instead of Zircaloy-2 tubes, with a characteristic of lower deuterium pick-up. The Zr-2.5 wt. % Nb pressure tubes had no formation of blisters except for local accumulation of hydrides in some of pressure tubes that have become in contact with the calandria tube.

For some of the early reactors, the garter springs were designed to be loose-fitted. However, these springs moved out of their design positions due to the sliding force exerted in the process of construction or to the vibration in operation. Therefore, with a view to preventing the contact of the pressure tube and the calandria one, the garter spring design changed from loose-fit to tightly-fit along with the change of the spring material from Zircaloy-2 to X-750. At the same time, the number of the spacers has increased to 4 from 2.

4.1.3. Rolled joint

The rolled joint is the part at which deuterium ingress is the largest and the residual tensile stress is the highest. This is why the rolled joint is noted as the most susceptible to DHC. In 1974 and 1975, some rolled joints in Pickering units 3 and 4 failed due to through-wall cracks by DHC.

The accidents were attributed to too high residual tensile stress formed at the rolled joint by an improper rolling process. About 70 tubes were replaced in Pickering units 3 and 4 [6].

Design changes have been introduced to reduce residual stress at the rolled joint as low as possible and to minimize the clearance between pressure tube and end fitting. The aim of the design changes is to lessen the probability of DHC due to high residual stress. Nontheless, the rolled joint is still more susceptible to DHC than the tube center due to higher tensile stress at the rolled joint and the larger deuterium ingress rate.

4.2. Irradiation Enhanced Deformation of Pressure Tube

Pressure tubes change their dimension as functions of temperature, stress and neutron flux. Therefore, fuel channels shall be designed to allow for their dimensional changes expected during 30 years of design life. The initial 6 CANDU units had no adequate design allowances for the dimensional changes because of no available data.

Based on periodic measurements performed on the fuel channels of Pickering and Bruce units and on out-pile data for over 20 years, equations for predicting pressure tube deformation have now been set up to predict the dimensional changes with time. However, since no CANDU reactor has yet operated for 30 years, it is important to carry out material testing to the high neutron fluencies in a test reactor of high neutron flux and to monitor the deformation of pressure tubes to ensure it remains as predicted. Typical dimensional change of a pressure tube is illustrated in figure 6, including sagging, elongation and diametral expansion [7].

4.2.1. Sagging

A pressure tube sags with time between the spacers due to the weight of fuel bundles and coolants it supports for its design life. The increase in the number of the spacers to 4 in later units, however, ensures that the pressure tube should not contact the calandria tube for more than the 30 year design life only if the spacers are held in their design positions.

In addition to the sagging of pressure tubes between the spacers, the entire fuel channel assembly also sags with time, resulting in the increase in its curvature with time. This curvature may interfere with the passage of fuel bundles and in an extreme case the fuel channel may touch the horizontal reactivity control system located at the right angles to the fuel channels. The gap between fuel channels and reactivity control systems shall be monitored in the last half of the design life for the lead unit.

4.2.2. Elongation and Diametral Expansion

Elongation of the pressure tube increases linearly with time as shown in figure 7 [3]. The rate of elongation is about 5 mm/year that is higher than expected in the design of early CANDU units [8]. Therefore, the early units has not had a sufficient margin for accommodating the elongation of pressure tubes for the design life of 30 years. All other CANDU units, however, have a bearing length of at least 75 mm at both tube ends which is considered sufficient to accommodate the elongation up to the end of life.

Diametral expansion of the pressure tube increases the amount of primary coolant flowing around the fuel bundles, reducing the critical channel power at constant flow. Though the power reduction can be offset by the flow redistribution between the high power channels and the low power channels, it will result in fuel cooling. Design allowance for diametral expansion, therefore, is limited to 5 % of the tube thickness. Figure 8 shows that the diametral expansion rate is about 0.1 mm/year.

4.3. Changes of Mechanical Properties in Pressure Tube

With neutron irradiation, pressure tubes become hardened along with the increase in strength and with the decrease in ductility and fracture toughness. In addition, the susceptibility to DHC and the crack propagation rate increase. However, testings on irradiated pressure tubes demonstrate that irradiation damage becomes saturated at a fluence of 0.5×10^{26} n/m^2 and no further change is observed up to 1×10^{26} n/m^2 as shown in figure 9 [3,9,10]. This saturation of irradiation damage may continue to the end of the design life so that Zr-2.5 % Nb pressure tube can withstand the 30 year design life, but no one can be sure of it.

When a flaw exists in a pressure tube, it is great concern if it can grow due to DHC with irradiation time. Thus, the tube with flaws need to be carefully monitored and observed with time. In order for tubes with surface flaws to continue operating, therefore, it is required that the assessments should be made to assure that no DHC will occur till the end of the next inspection period and also that if DHC occurs, there would be detectable leak and the reactor safely shutdown before this cracking becomes unstable. To ensure this LBB requirement for pressure tubes is satisfied, there must be a high confidence level that after a crack starts to leak the time available to detect this leakage and take appropriate action will exceed the time required for the crack to grow to an unstable length. Annulus gas system is a safety system to detect leakage of the pressure tube, which guarantees the LBB requirement to be fulfilled during the design life of pressure tubes.

If a flaw initiates and propagates, it is desirable to increase fracture toughness of Zr-2.5 % Nb pressure tubes to guarantee the LBB. In practicality, fracture toughness of the irradiated pressure tubes showed a wide range of values. Some of pressure tubes maintained high fracture toughness even after 18 years of operation. Recent researches to understand the variability of fracture toughness leads to a conclusion that the minimization of the trace elements such as chlorine, phosphorus and carbon results in high fracture toughness as shown in figure 10 [1]. As a result, quadruple melting is introduced to reduce the chlorine content and thus increase fracture toughness of pressure tubes.

4.4. Aging of the Calandria

Calandria vessel, end shields and calandria supports are the large and permanent components contained in the reactor building. These components are designed to function without maintenance till the end of the reactor life. Therefore, maintenance of their integrity is a limiting factor in reaching the design life of the unit and in extending its life. Followings are describing the mechanisms degrading reactor assembly components.

4.4.1. Irradiation Embrittlement

Reactor assembly including Calandria vessel and other associated structure components are made of 304 austenitic stainless steel and 308L filler material for weldments. It is reported that the degree of irradiation embrittlement of those components depends on the temperature of irradiation and on the cumulative fluence [12]. Further, weld metal is degraded more easily and is more susceptible to embrittlement. This is due to delta ferrite formed in the weldment that acts to prevent cracking in the solidification of weld pool. High fast neutron flux regions in a calandria are listed as follows;

-corners among main shell, annular plate and subcell

-the center of the calandria tube sheet (due to no other reflector installed)

Though the calandria tubes of full-annealed Zircaloy-2 become hardened and embrittled by irradiation during operation, sufficient amount of data taken from irradiated calandria tubes assures that the calandria tube functions its role for 30 year design life.

4.4.2. Corrosion and Fatigue

The design of the calandria/end shield support assembly in CANDU 6 comprises an annular gap between the embeddment ring and the calandria support plate. This gap space is filled with lead wool and stainless steel wire. 3 units of CANDU 6 design experienced the accident that water was detected in this gap. Accumulation of water in the gap offers a serious potential risk of corrosion. Radiolysis of air and water may cause the formation of nitric acid, leading to stress corrosion cracking of the carbon steel component and galvanic corrosion of the weldment of stainless steel components. Drainage to the annular gap is incorporated in the modified design of CANDU 6 calandria support.

Under normal operating condition, there is little change in the pressure exerting on the calandria vessel, calandria tubes and end shields. It is estimated that about 150 cycles of pressure change may occur during the design life of 30 years. Anticipated total number of thermal cycles in the design life is 5100 for the level A condition and 710 for the level B condition. Fatigue analysis is performed in accordance with the requirements of the ASME code section III, Division 1, Paragraph NC-3219.2. This evaluation concludes that a detailed fatigue analysis is not required [13].

In all CANDU units except for Bruce A reactors, the moderator inlet nozzles are designed in a fan shape such that moderator flow should be distributed evenly in the calandria and that flow impingement should not induce calandria tube vibration. Nozzle deflector has a potential risk to be damaged by high cycle fatigue due to flow induced vibration.

4.4.3. Stress Relaxation and Sagging of Calandria Tube

Calandria tube rolled joint is in a sandwich type joint such that the calandria tube be squeezed between the calandria insert and the calandria tube-sheet bore. Since the joint forms part of the pressure boundary, it should be leak-tight. Furthermore, these joints must have adequate pull-out strength.

Residual stress in the joint is relaxed by aging and irradiation. The stress relaxation makes the joint strength between the calandria tube and tube-sheet bore decreasing, degrading the integrity of the joint after all.

A leak at the calandria tube joint can be detected by monitoring the change of the moisture content in the annulus gas system. There has been no cases of calandria tube joint leakage so far.

Heavy pressure tube containing fuel bundles sags itself and makes a calandria tube sag consequently. The calandria tube can eventually touch the liquid injection shutdown system unit nozzle and can induce fretting wear on tube and nozzle. For the calandria tube which is not located on the poison injection unit nozzle, calandria tube sagging is not regarded as a problem until it limits fuel bundles passing through the pressure tube or until it impedes pressure tube exchange.

5. INSPECTION AND MONITORING FOR PRESSURE TUBES

Canadian Standards Association (CSA) Periodic Inspection Program (PIP) described in CSA-N285.4 stipulates the number of pressure tubes to be required for periodic inspection in each unit in oder to find an unexpected problem. This program includes the surveillance testing to confirm if the predictions derived from the design are consistent with the changes of the mechanical properties of the pressure tubes. Reactor operators may perform an additional in-service inspection in order to supplement monitoring the pressure tube properties.

Followings are describing the testing and inspection techniques monitoring fuel channel components.

5.1. Pressure Tube Flaw Detection

In-service volumetric inspection of pressure tubes was considered unnecessary before 1974. They believed that a flaw would not be generated during operation as long as the external inspection of the pressure tubes could prove no flaws during manufacturing. In 1974, however, several pressure tubes were found to leak in Pickering units 3 and 4 and the cause was found to be due to the cracks developed at the rolled joints [14]. This was the turning-point of the in-service inspection.

Pre-service eddy current inspection of Bruce units 1 and 2 detected a laminated defect in a tube. It was confirmed by a careful investigation that the defect was introduced in the manufacturing process with no detection during the manufacturer's inspection. Changes have been made continuously in the procedures of tube manufacturing and inspection in order to avoid reoccurrence of this type of manufacturing flaw.

The development of rolled joint cracks and manufacturing flaws has prompted to develop a new inspection system. Thus, AECL has developed the CIGAR (Channel Inspection and Gauging Apparatus for Reactor) system [15] that started into service from 1985 and it has become the major inspection and gauging system for the pressure tube in operation since then.

In 1986, Bruce unit 2 was shutdown safely when leak was found in the tube N06. However, this tube was ruptured later in the process of low temperature pressurization to locate the leaking channel by growing the crack. The leaking was found to be attributed to the growing crack from manufacturing lamination defects. Therefore, much attention was focused as to whether this kind of manufacturing defects can exist on pressure tubes operating in Bruce units 1 and 2, and Pickering units 3 and 4. Consequently, an in-service inspection program started to carry out full length volumetric inspection to all the pressure tubes in operation by using the CIGAR. In addition, off-cuts of pressure tubes had to be inspected. This reinspection adopted a high frequency (100 MHz) ultrasonic method with increased detection sensitivity of manufacturing flaws. The new inspection system that has been developed lately is PIPE (Package Inspection Probe) that can inspect 24 of rolled joints. This system was applied for the first time in Bruce unit 2 in 1987.

Before CIGAR system was introduced, the Dry Channel Gauging Equipment was used for periodic inspection of pressure tubes with the surface profilometer of strain gauge stylus type. Its primary function was to monitor the depth of fretting marks by fuel bundle bearing pads and the fuelling scratches. Then, LVDT (Linear Variable Differential Transformer) stylus type profilometer operable even in water filled channels was developed for CIGAR and it was successfully used in measuring the depth of fret marks identified by the ultrasonic flaw detection system. Many other surface inspection systems have been developed ever since the fretting problems occurring in Pickering unit 8.

A visual inspection capability based on the radiation resistant hermetically sealed CCTV system has been developed and applied to many pressure tubes for in-service inspection assessment. The camera head attached to the AECL-SAR-STEM must be used in an isolated and drained channel. Head positioning, light intensity, focus adjustment and data recording must be controlled from the outside of the containment. Recently, the new camera system operable in water along with CIGAR was developed. This allows wider use of visual inspection in water by saving time to take the channels out of water and simultaneously reducing the amount of personal radiation exposure.

5.2 Geometry Monitoring

Pressure tube diametral change should be monitored periodically to assure that diametral creep and growth meet the design allowances. The CIGAR used the ultrasonic gauging system to measure diameter and wall thickness at 60 locations around a tube for 3mm axial intervals along the length.

The pressure tube displacement profile and the maximum vertical deflection, i.e., sag are to be measured periodically. The deflection is measured in many positions along the tube length by using the servo inclinometer in CIGAR and the displacement profile is calculated by a single integration. Maximum pressure tube sagging in a dry channel can also be measured by the laser which is aligned to the center of the end fittings. The amount of sagging is determined from the difference at the two spots in the elevation of laser beam.

Within a few years of operation in the early Pickering units, pressure tubes were found to be elongated larger and faster than was expected. Manual operation 'Spot Face Tools' allows to measure a distance from the end fitting for each spot faces in the reactor end shield.

5.3. Spacers, Blisters and Hydrogen Measurement

Eddy current devices were developed after the failure of the pressure tube G16 in Pickering unit 2 in 1983 and is now used in the in-service and periodic inspections.

The spacer location coils and CIGAR ultrasonic flaw detection system have become the primary inspection tools. Ultrasonic inspection provides high response in measuring a gap between the tube and the spacer and in detecting cracks in the blisters.

No blister has been found in the operating Zr-2.5Nb tubes yet. However, many laboratory results show that blisters can occur at the tube contact spots. Therefore, the displacement of the spacers causing a contact between pressure tube and calandria tube are considered undesirable. Consequently, a SLAR (Spacer Location And Repositioning) system has been developed by COG (CANDU Owner's Group)l. It was, though, pointed out that the SLAR system may induce significant bending stress in the pressure tube during the spacer repositioning operation. If blisters are present in a tube, this bending stress might cause them to crack or to accelerate the crack propagation. The fastscan blister detection system was developed where six line focused ultrasonic transducers was used to inspect the outside surface of pressure tubes.

BLIP (Blister and Spacer Location Inspection with Pipe), which adopted the SLAR [16] type fastscan blister detection system in association with the CIGAR spacer detection system, was developed to locate blisters and spacers quickly. However, repositioning the spacers by the SLAR needs to keep the pressure tube and calandria tube centralized in advance. The gap measurement system which used both eddy current and ultrasonic inspection [17] was also developed to monitor a gap. Eddy current technique is used as the primary tool and ultrasonic inspection is supplementary in measuring the gap and the variation of the tube wall thickness.

Deuterium ingress is the most important parameter in predicting the formation of brittle hydride blisters at the contact between a pressure tube and calandria tube. Therefore, sufficient amount of data is needed for the lead CANDU reactors since deuterium ingress is not easily simulated in the out-pile tests. A sampling tool was developed to scrape metal slivers from the wall of pressure tubes, leaving a round and smooth groove whose depth is smaller than the corrosion and wear allowance [18].

6. LIFE MANAGEMENT STRATEGY FOR PRESSURE TUBES

Pressure tubes are one of the most major components for the life management of CANDU reactors. However, there have been some unexpected problems associated with the pressure tube in the early CANDU units. These experiences and the information gained from the out-pile tests have become the basis in understanding their in-reactor performances and in establishing the service guidelines to manage the aging of pressure tubes. Furthermore, these have allowed evolutionary design improvement of pressure tubes to be developed for the more recently built fuel channels.

The most important behaviors that have not been anticipated during the design of the initial CANDU fuel channels are:

Irradiation enhanced deformation

Delayed Hydride Cracking.

The another fundamental factor that has the strong potential to affect the life of Zr-2.5 % Nb pressure tubes, and reduced the acceptable lifetime of Zircaloy-2 pressure tubes to significantly less than 30 year design life for CANDU fuel channels, is: degradation of pressure tube material properties with neutron irradiation or operation.

These aging phenomena are to be monitored periodically. Since the pressure tubes are designed to fully function for the design life of 30 years, the actions shall be taken to mitigate three key aging phenomena of pressure tubes

6.1. Delayed Hydride Cracking (DHC)

DHC is a primary aging concern of pressure tubes. Thus, it is required to prohibit the formation of any hydrides in the pressure tube because the initiation or propagation of a crack has been related to hydrides precipitated near the crack tip. To minimize the possibility of hydrides formed, it is important to avoid any conditions that cause local concentrations of hydrogen/deuterium in a tube such as: tensile stress concentrations, and temperature gradient. Tensile stress concentrations are minimized by assuring that any flaws or defects are not generated during tube manufacturing, installation, commissioning or operation. The improper roll joining induced very large residual tensile at the rolled joint, resulting in leaking of some pressure tubes due to DHC. This crack initiation source was removed later by improving the roll joining method such that tensile residual stress is below the threshold limit for the initiation of DHC.

The current concern associated with operating pressure tubes is the local accumulation of hydrides or the brittle hydride blisters that may form at the cold contact spots. Though the CANDU pressure tubes operating currently have four spacers installed instead of 2 spacers with a view to preventing their contact with the calandria tubes, the contacts between pressure tube and calandria one likely can not be avoided. Therefore, the contents of hydrogen accumulated at the contact spots shall be monitored and conservatively calculated. In case the hydrogen content at the contacts may exceed the blister formation threshold (BFT), remedial action must be taken prior to fast brittle rupture. In other words, current understanding of this criteria limits the allowable lifetime for currently operating Zr-2.5 % Nb pressure tubes in contact with the cooler calandria tube to 15 and 20 years. To achieve their 30 year design life, all CANDU fuel channels with 4 potentially displaced spacers will require spacer relocation by using the SLAR after operating for around half of this design life. On the other hand, the best way to completely eliminate a concern associated with DHC is to lower the total hydrogen content absorbed during the 30 year design life to less than TSS at the operating temperatures. Much effort has been made to reduce the initial hydrogen content to less than 5 ppm or to make the hydrogen concentration at the rolled joints more uniform.

6.2. Irradiation Enhanced Deformation

When the earliest CANDU reactors were built, there was no available data associated with the irradiation enhanced deformation behavior of pressure tubes occurring at high fluencies. Therefore, allowances were not made for the amount of pressure tube deformation for the earliest units.

As a result, all fuel channels in Pickering units 1 to 4 were replaced. Since then, all the CANDU units except for the earliest units were designed to assure enough margins related to irradiation enhanced deformation so that they are expected to be able to accomodate 30 years of pressure tube deformation. However, since no CANDU pressure tubes have yet reached neutron fluence corresponding to the end of life, material testing to high fluencies should be conducted in parallel for the life management.

6.3. Changes of Material Properties in Pressure Tube

Fracture toughness of pressure tubes drastically decreased to the fluence of $1x10^{26}$ n/m^2 and then became saturated. In contrast, their strength increased very rapidly at the initial stage of irradiation and became flattened at over this fluence [9]. These results show that pressure tubes degrades with neutron fluence, leading to the decrease of their safety margin. Thus, when a sufficient large flaw is present on a pressure tube, an conservative assessment should be made to assure that DHC will not occur till the next inspection period and that as a defence in depth, even if DHC did occur, the LBB condition is observed: as the leaking crack would be detected by the Annulus Gas System and the reactor safely shutdown before this cracking becomes unstable. Therefore, for assessment of pressure tube integrity to be more correct, a good data base is indispensable for the properties of irradiated pressure tubes with neutron irradiation.

The material properties of Zr-2.5 % Nb pressure tubes after 30 years of operation are expected to be acceptable, since these property values change significantly only during the first few years of irradiation. Hence, the properties for the pressure tube now operating in all CANDU units are considered adequate to allow them to achieve their 30 year design life. However, as no CANDU reactor has yest operated for 30 year design life, material testing to high fluencies should follow with monitoring fracture properties of CANDU pressure tubes continuously.

7. CANDU REACTORS IN KOREA

Two CANDUs, Wolsong unit 1 and 2, are in commercial operation in Korea and two others, Wolsong units 3 and 4, are under construction. Since Wolsong unit 1 entered into commercial operation in 1983, it has recorded very high availability. Many problems related to pressure tubes have been, however, found by the CIGAR inspections conducted three times from 1990 to 1994.

In Wolsong unit 1 in which the pressure tubes of 25 different heats were installed, 47 channels (12.4 %) were found to elongate over 60 mm at 3,784 EFPD (May 9, 1995) and a pressure tube (H-16) was found to have the maximum deformation of 67.9 mm. Figure 11 shows the elongation in the pressure tubes in Wolsong unit 1 that has the channel power dependence [19]. It is planned that the deformation of the pressure tubes will continue to be monitored with increasing time.

The CIGAR inspection results show that 13 out of 39 pressure tubes (33.3 %) was found in contact with the calandria tubes. It is a serious concern that a large number of pressure tubes are in contact with the calandria tube. Most of them had the garter springs displaced out of their design positions, causing their sagging. Therefore, for the sake of LBB, the contacts will be eliminated by the SLAR (Spacer Location And Repositioning).

Surface flaws also were found on 23 pressure tubes out of 39 CIGAR channels. Though the cause for the surface flaws is not well defined yet, those defects seem to be due to the debris fretting circulating in the primary heat transport system. Three dispositionable tubes were replaced in 1994 and others having defects on the inner surface will be monitored continuously and DHC will be assessed in order to ensure the operational safety.

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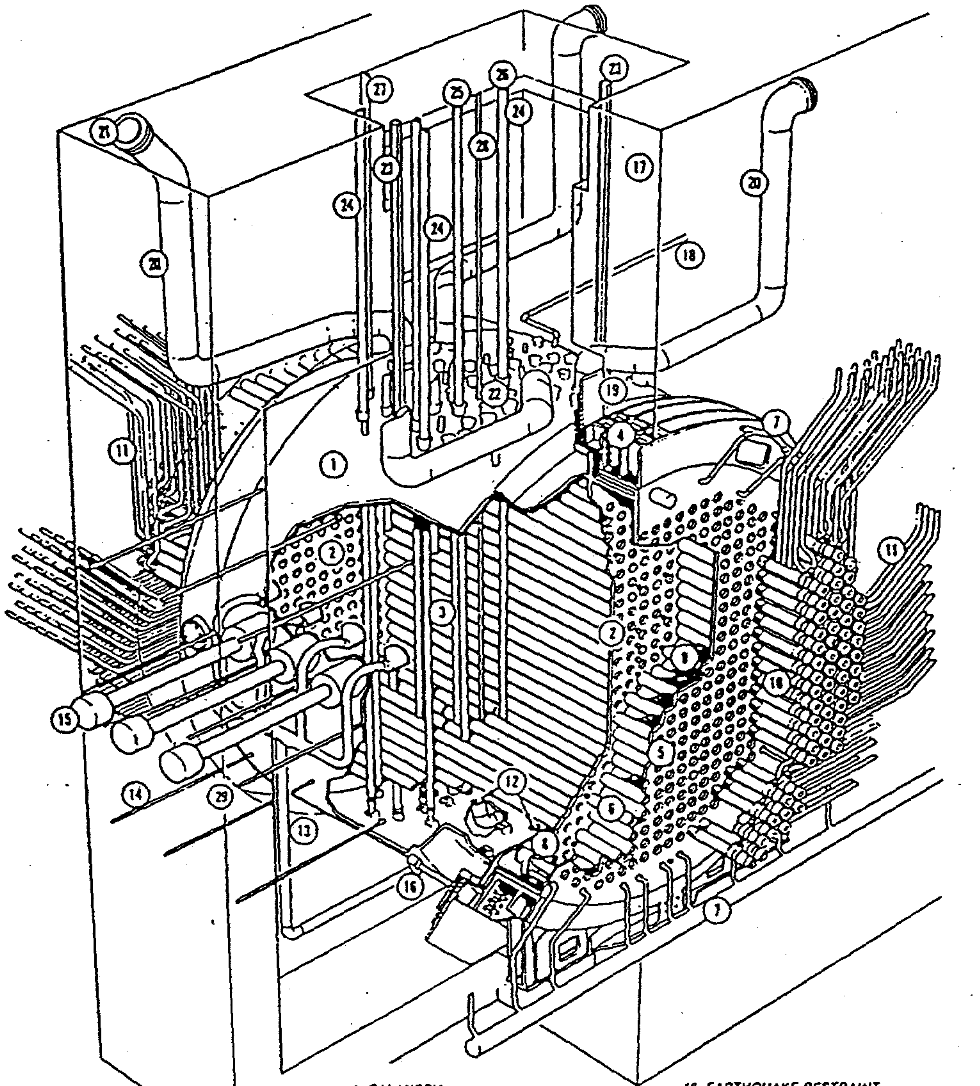
Table 2 Summary of Failure Experience in CANDU Pressure Tube

CANDU Unit	Failure Cause	Failure Mechanism	Action	Date
Pickering-3	Over extended rolled joint	DHC	17 Pressure tubes were replaced	1974.8
Pickering-4	Over extended rolled joint	DHC	52 Pressure tubes were replaced	1975.5
Bruce-2	Over extended rolled joint	DHC	2 Pressure tubes were replaced	1982.2
Pickering-2	Sagging(G-16)	Hydride Blister	Whole channel were replaced	1983.8
Pickering-3	Over extended rolled joint	DHC	1 Pressure tube was replaced	1985.
Bruce-2	Fabrication defect (No 6 PT/CT)	DHC	1 PT/CT were replaced	1986.3

Table 1 Operating Units of CANDU Reactors

CANDU Unit	No. of Fuel Channels	Power Output (MW)	In-Service Date
Pickering 1	390	515	1971
Pickering 2	390	515	1971
Pickering 3	390	515	1972
Pickering 4	390	515	1973
Bruce 1	480	850	1977
Bruce 2	480	850	1977
Bruce 3	480	850	1978
Bruce 4	480	850	1979
Pickering 6	380	515	1982
Point Lepreau	380	680	1983
Gentilly, Quebec	380	680	1983
Wolsong 1, Korea	380	680	1983
Embalse, Argentina	380	680	1984
Pickering 5	380	515	1984
Bruce 6	480	850	1984
Pickering 7	380	515	1985
Bruce 5	480	850	1985
Pickering 8	380	515	1986
Bruce 7	480	850	1986
Bruce 8	480	850	1987
Darlington 2	480	850	1990
Darlington 1	480	850	1992
Darlington 3	480	850	1992
Darlington 4	480	850	1993



1 CALANDRIA
2 CALANDRIA — SIDE TUBESHEET
3 CALANDRIA TUBES
4 EMBEDMENT RING
5 FUELLING MACHINE — SIDE TUBESHEET
6 END SHIELD LATTICE TUBES
7 END SHIELD COOLING PIPES
8 INLET-OUTLET STRAINER
9 STEEL BALL SHIELDING
10 END FITTINGS
11 FEEDER PIPES
12 MODERATOR OUTLET
13 MODERATOR INLET
14 HORIZONTAL FLUX DETECTOR UNIT
15 ION CHAMBER
16 EARTHQUAKE RESTRAINT
17 CALANDRIA VAULT WALL
18 MODERATOR EXPANSION TO HEAD TANK
19 CURTAIN SHIELDING SLABS
20 PRESSURE RELIEF PIPES
21 RUPTURE DISC
22 REACTIVITY CONTROL UNIT NOZZLES
23 VIEWING PORT
24 SHUTOFF UNIT
25 ADJUSTER UNIT
26 CONTROL ABSORBER UNIT
27 ZONE CONTROL UNIT
28 VERTICAL FLUX DETECTOR UNIT
29 LIQUID INJECTION SHUTDOWN NOZZLE

Figure 1 CANDU 6 Reactor assembly

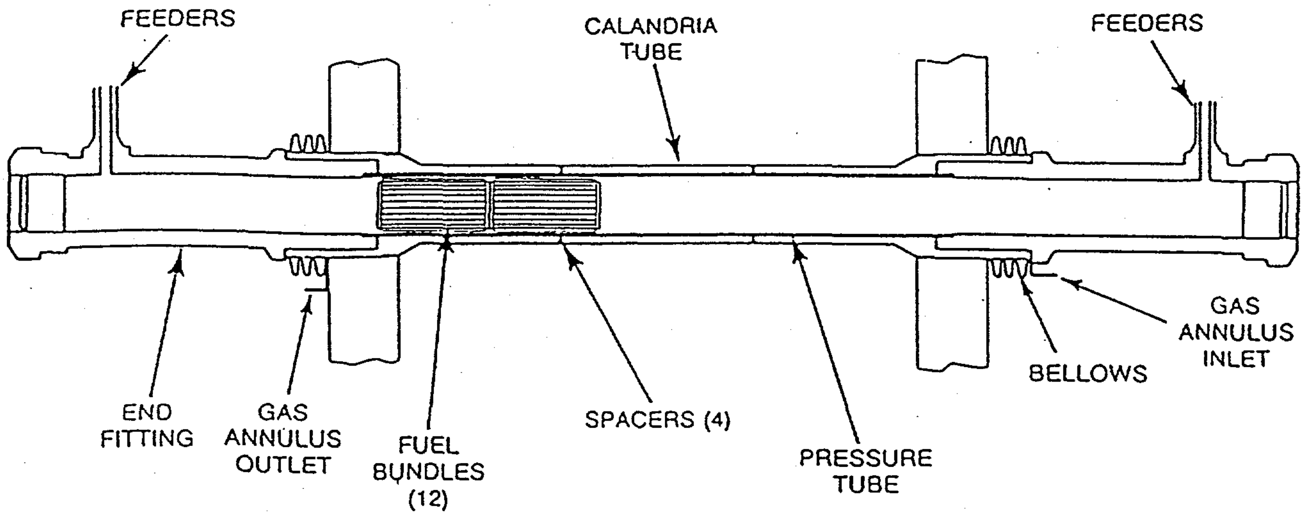


Figure 2 Simplified description of fuel channel

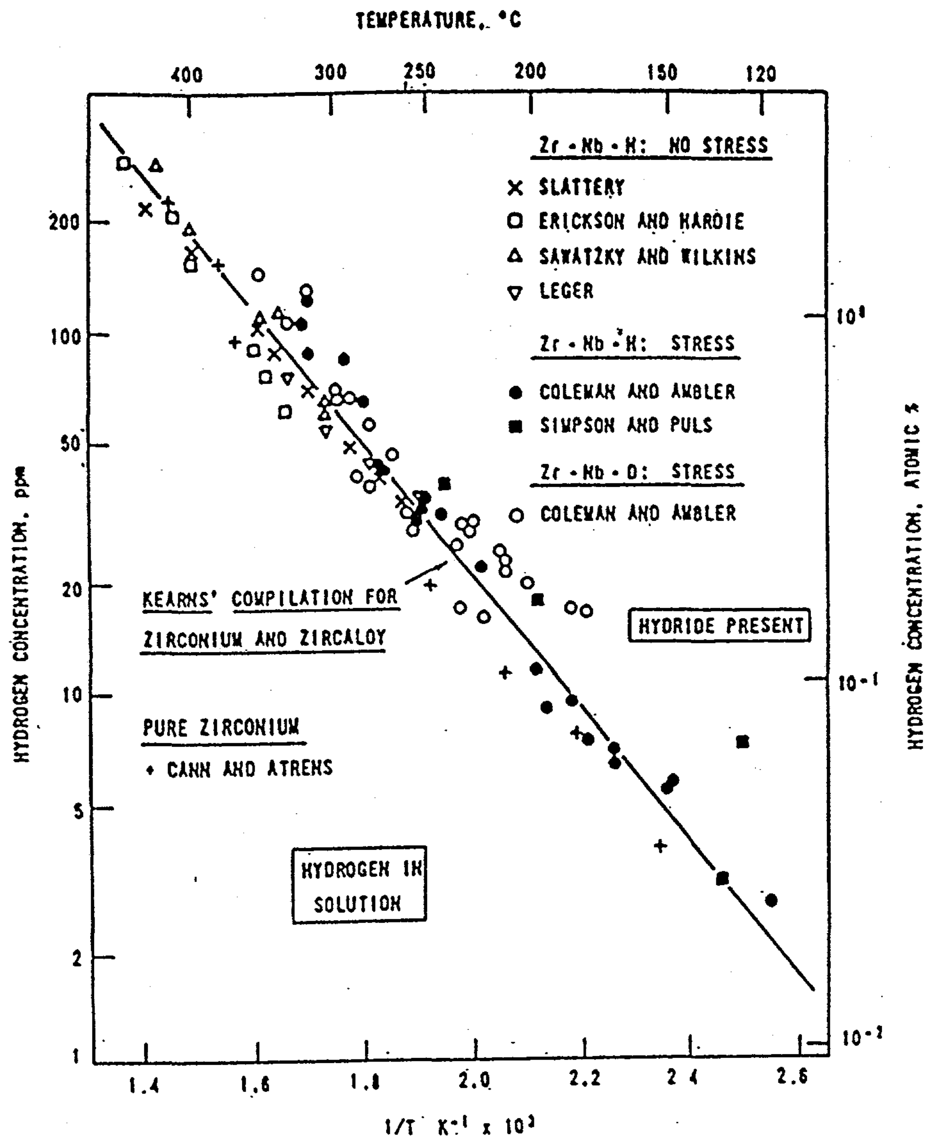


Figure 3 Summary of termial solubility of hydrogen isotopes in cold-worked Zr-2.5wt% Nb

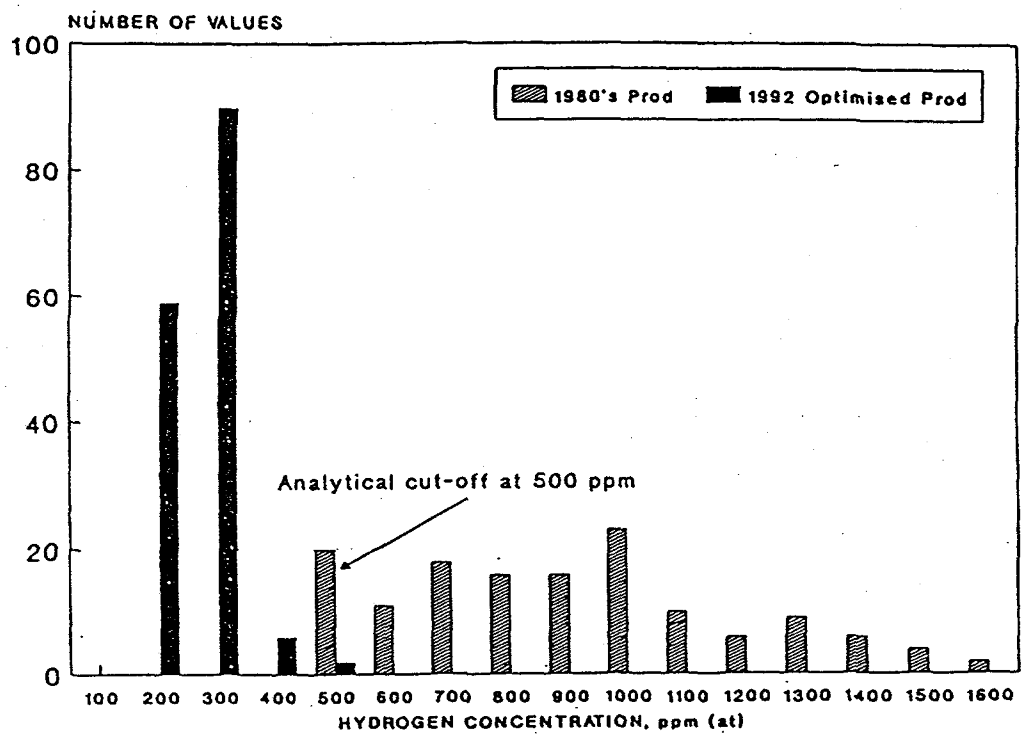


Figure 4 Histogram of hydrogen concentrations for pressure tubes manufactured in the 1980s and 1992[1]

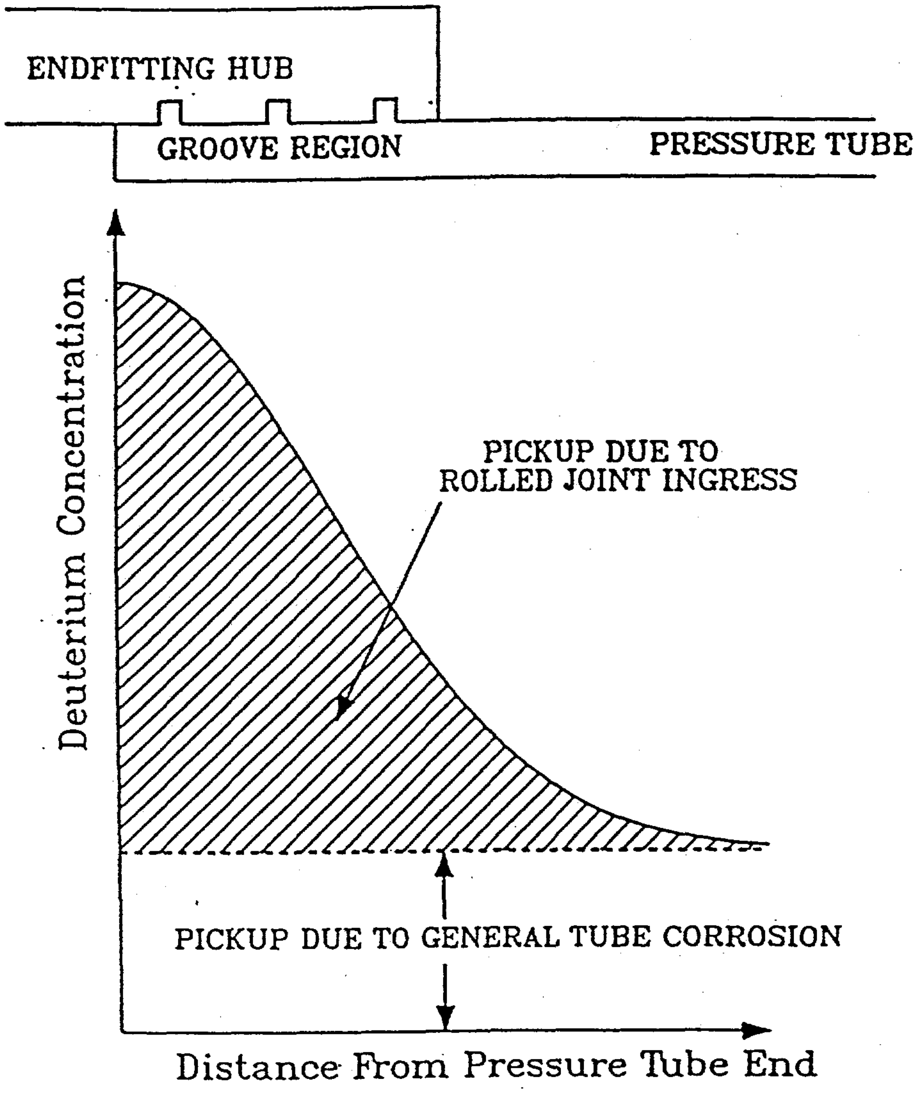


Figure 5 A schematic diagram of the deuterium concentration profile at the end of the pressure tube showing the contribution from deuterium ingress at the rolled joint and pickup due to corrosion along the pressure tube[4]

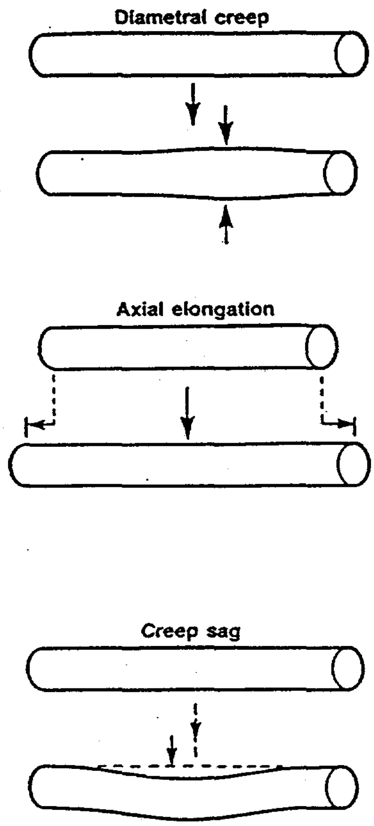


Figure 6 Dimensional changes in pressure tubes

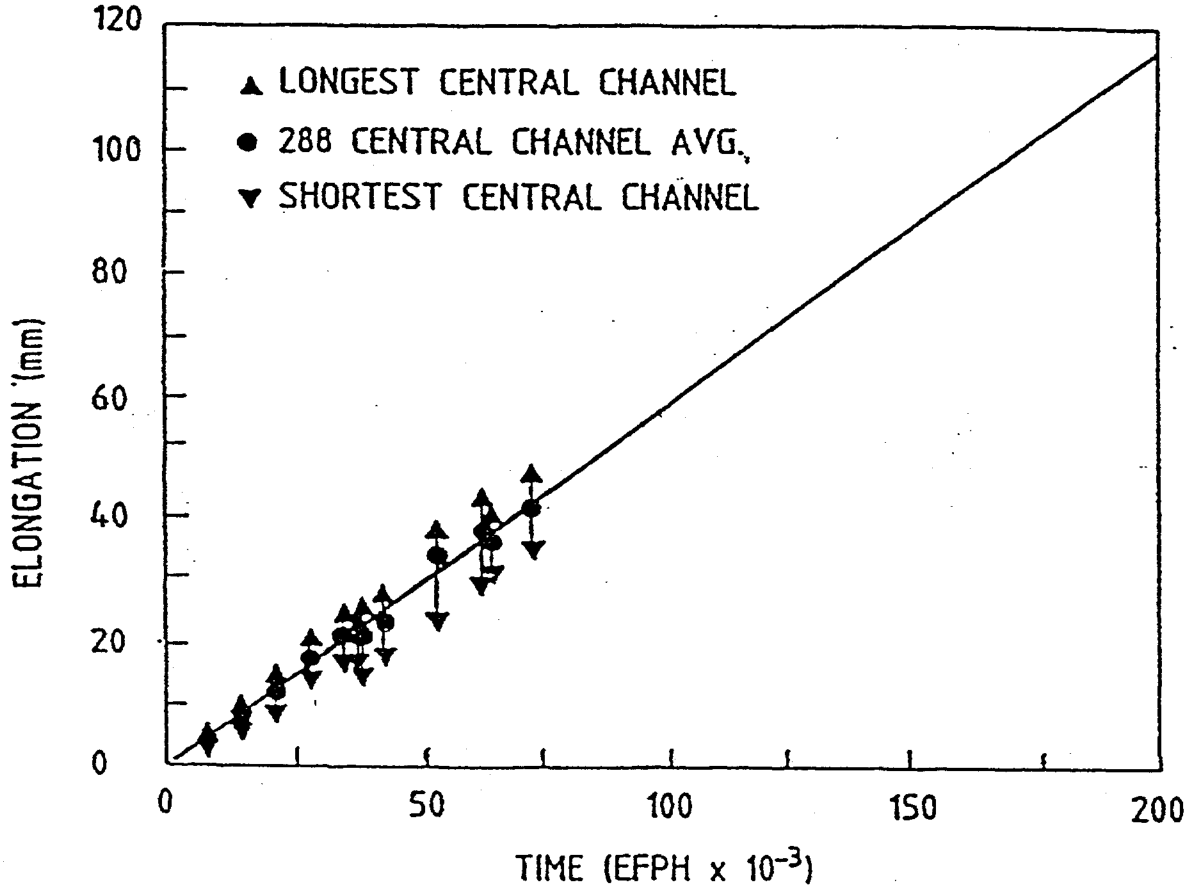


Figure 7 Elongation of BNGS 'A' pressure tubes as a function of time[3]

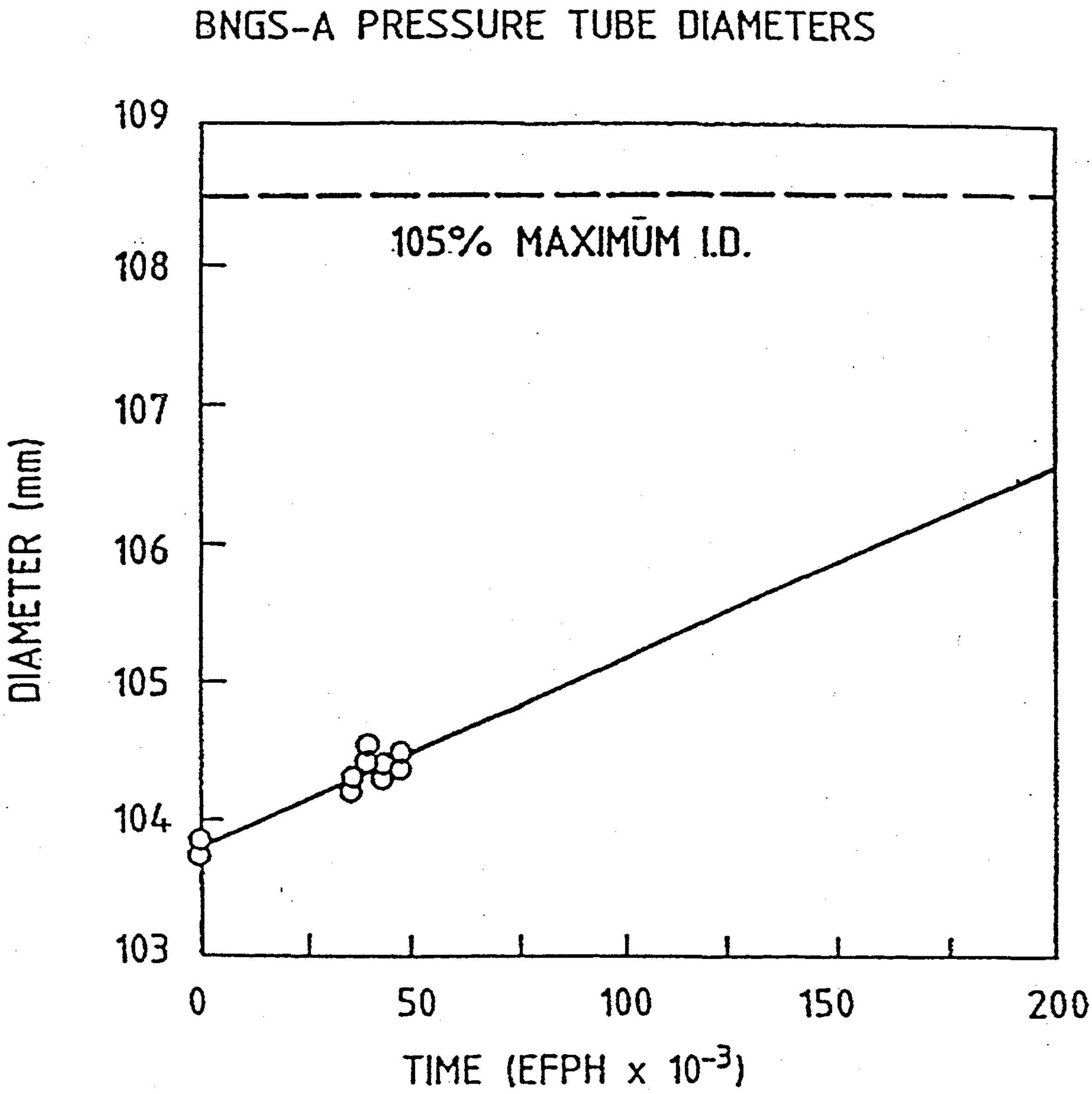


Figure 8 Increase in diameter of BNGS 'A' pressure tubes as a function of time[3]

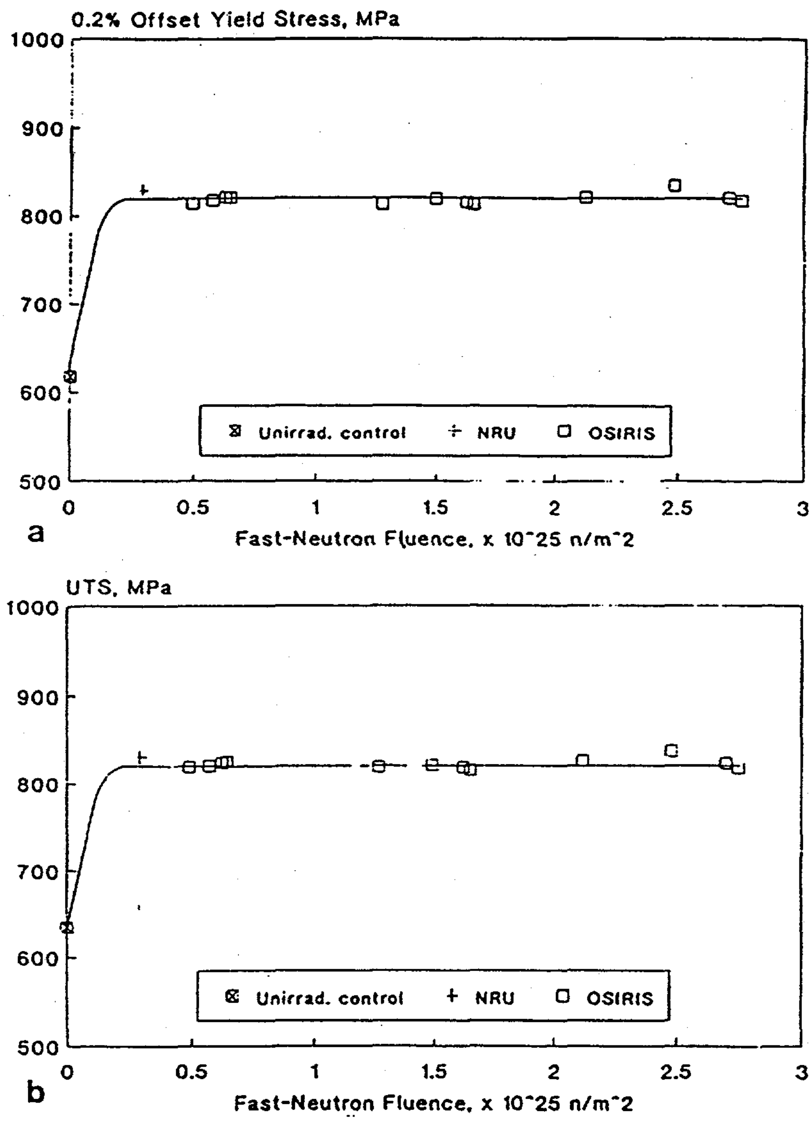


Figure 9 Effect of neutron fluence on transverse tensile strenth of tube H737 at 240℃ (preselected material irradiated in OSIRIS and NRU at 250/255℃) :(a) 0.2% offset yeild stress and (b) ultimate tensile strength [9].

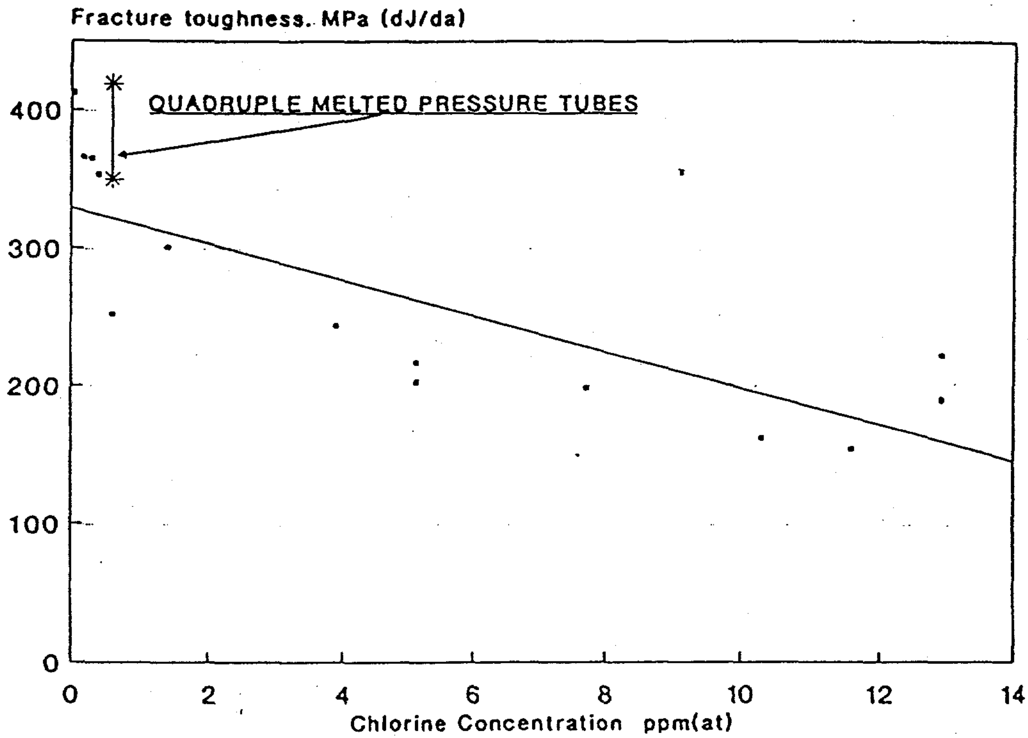


Figure 10 Fracture toughness as a function of chlorine concentration for pressure tubes with phosphorus concentrations of 〈30 ppm (at) [1]

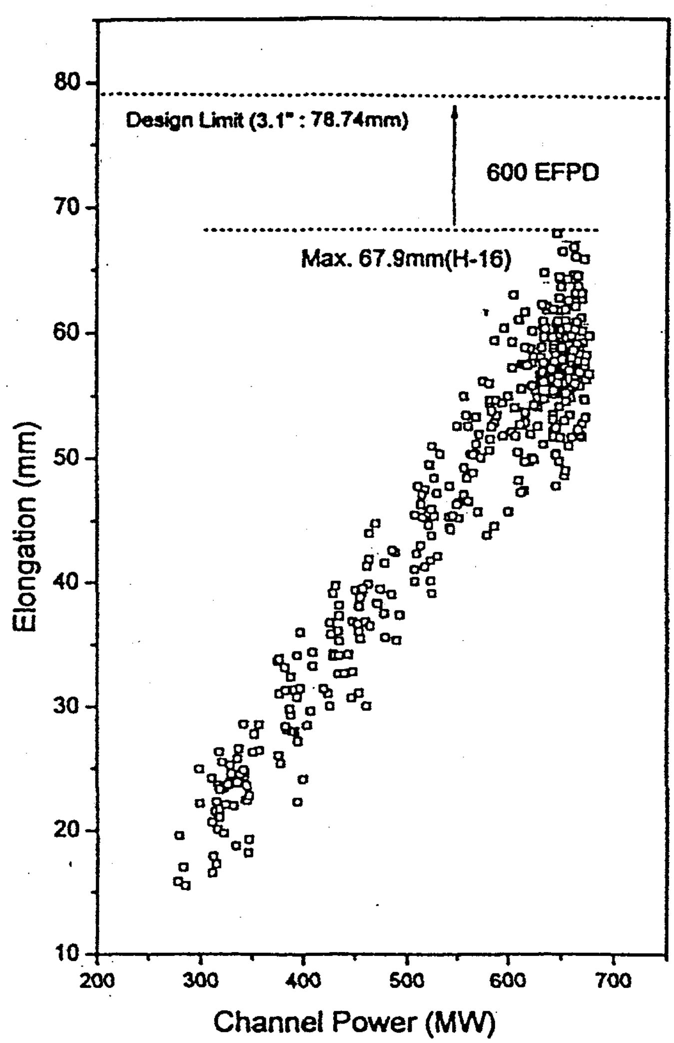


Figure 11 Channel power dependence of WS-1 pressure tubes elongation for 3784 EFPD(1995. 5. 9.)

서 지 정 보 양 식

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제목 / 부제

Plant Life Management Strategies for Pressurized Heavy Water Reactors

연구책임자 및 부서명	김영석
연 구 자 및 부 서 명	

권상철, 주기남, 정용환, 국일현

출 판 지	대전	발행기관	한국원자력연구소	발행년	1998
페 이 지	36 p.	도 표	있음(0), 없음( )	크 기	26 Cm.
참고사항					

비밀여부	공개(0), 대외비( ), __ 급비밀	보고서종류	기술보고서
연구위탁기관		계약 번호	

초록 (15-20줄내외)

CANDU형 가압중수로 발전로의 수명에 가장 영향을 미치는 핵심부품-압력관, 캘란드리아 관, end fitting, 핵연료 스페이서 및 캘란드리아-들의 주요 노화현상에 대한 기술현황 분석을 수행하였다. 특히 압력관의 노화현상을 감시하고 시험할 수 있는 감시시험 방법도 검토하였다. 따라서 본 연구에서는 CANDU형 가압중수로 발전로에서 가장 핵심부품인 압력관의 수명관리 방안이 Leak-Before-Break, Delayed Hydride Cracking, 중성자 선량에 따른 가속화된 크립 및 물성변화등의 경험자료의 검토를 토대로 제시되었다.

주제명키워드 (10단어내외)	CANDU, Pressure Tubes, Life Management, Delayed Hydride Crakcing, Calandria, inspection and monitoring, Blisters,
Leak-Before-Break,	Rolled joint, Ageing, Aging mechanism

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Abstract (15-20 Lines)

This technical report reviewed aging mechanism of the major components of CANDU 6 reactor such as pressure tubes, calandria tube, end fitting, fuel channel spacer and calandria. Furthermore, the surveillance methodology was described for monitoring and inspection of these core components. Based on the in-reactor performances data such as delayed hydride cracking, leak-before-break, enhanced deformation-creep and growth, the life management of pressure tubes was illustrated in this report.

Subject Keywords (About 10 words)	CANDU, pressure tubes, life management, delayed hydride cracking, calandria, inspection and monitoring, Blisters
leak-before-break	rolled joint, ageing, ageing mechanism